

Fermi National Accelerator Laboratory

FERMILAB-Conf-96/246-E

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**Jet Angular Decorrelation and Color Coherence
in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV**

James Jaques

For the D0 Collaboration

*Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510*

*Department of Physics, University of Notre Dame
Notre Dame, Indiana 46556*

August 1996

Published Proceedings of the *XI Topical Workshop on pbarp Collider Physics*,
Abano Terme (Padova), Italy, May 26-June 1, 1996

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**JET ANGULAR DECORRELATION AND COLOR
COHERENCE IN $p\bar{p}$ COLLISIONS
AT $\sqrt{s} = 1.8\text{TeV}$**

JAMES JAQUES
(for the DØ collaboration)
*Department of Physics, University of Notre Dame
Notre Dame, Indiana, 46556, USA*

Abstract

We present three QCD studies based on data collected by the DØ detector during the 1992–1993 and 1994–1995 runs of the Fermilab Tevatron collider at a center-of-mass energy $\sqrt{s} = 1.8\text{ TeV}$. The first study is an analysis of jet–jet azimuthal decorrelation as a function of jet rapidity separation. The second and third studies are probes of color coherence effects in hadronic collisions – one using multi-jet events and the other using W +jet events.

1 Soft Gluon Resummation

The *semihard region* of hadronic collisions, where $\sqrt{\hat{s}} \gg Q \sim E_T$, corresponds to jet production with large rapidity separations. In this region, large logarithms of the form $\ln(\hat{s}/Q^2)$ (where $\hat{s} \equiv$ partonic center-of-mass energy squared) may appear in perturbative calculations, corresponding to soft gluon emission. These can be resummed using the BFKL technique¹ and are expected to decorrelate the transverse energy (E_T) and azimuthal angle (ϕ) of the produced jets as the rapidity interval increases between them. We present the results from a study² of ϕ decorrelation between jets with large pseudo-rapidity interval, $\Delta\eta = \eta_1 - \eta_2$, as a function of $\Delta\eta$. Data distributions are compared to predictions from BFKL resummation, HERWIG³ (a LO Monte Carlo generator which employs Altarelli-Parisi parton evolution followed by Cluster fragmentation), and JETRAD⁴ (a parton-level NLO calculation).

The data were taken during the 1992–1993 initial run of the DØ experiment. The detector is described elsewhere⁵. This analysis selected events with at least two jets with $E_T > 20\text{ GeV}$, where the jets were reconstructed using a fixed-cone clustering algorithm with cone radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$. The most forward and most backward jets were selected, and one of the two was required to have $E_T > 50\text{ GeV}$ to avoid trigger biases.

DØ results for the ϕ decorrelation are shown in Figs. 1a and 1b. Fig. 1a shows distributions of $(1 - \Delta\phi/\pi)$, with $\Delta\phi = |\phi_1 - \phi_2|$, for three different

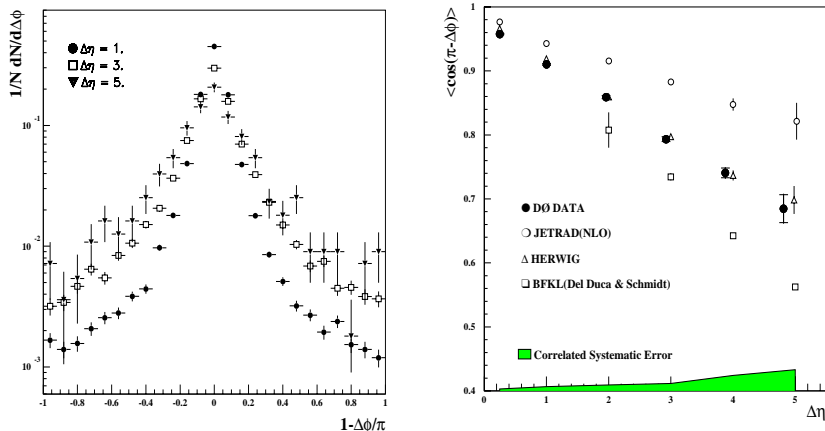


Figure 1: a) $1 - \frac{\Delta\phi}{\pi}$ distributions for three pseudorapidity intervals of the tagged jets. b) $\langle \cos(\pi - \Delta\phi) \rangle$ as a function of $\Delta\eta$ of the tagged jets for data and for the predictions of HERWIG and JETRAD simulations. The BFKL prediction is shown with the shaded band. The error bars shown on the data points represent statistical and systematic errors.

pseudorapidity intervals of the tagged jets. The increasing width of the $\Delta\phi$ distributions demonstrates jet azimuthal decorrelation with greater separation in η . Fig. 1b illustrates how the value of $\langle \cos(\pi - \Delta\phi) \rangle$ varies as a function of $\Delta\eta$ for data and several theoretical calculations. The steady reduction of this value indicates decorrelation increasing with $\Delta\eta$. The JETRAD NLO prediction underestimates the rate of decorrelation as a function of $\Delta\eta$. In contrast, HERWIG simulations at the particle level reproduce the observed decorrelation reasonably well. Finally, the BFKL calculations by Del Duca and Schmidt¹ predict too much decorrelation.

2 COLOR COHERENCE

Color coherence is defined as constructive and destructive interference among the amplitudes for soft gluons radiated from color-connected partons during the parton cascade process^{6,7}. An important consequence of color coherence is the *Angular Ordering* (AO) approximation of the sequential parton decays. AO is a leading- N_c (number of colors) approximation which requires that opening angles decrease uniformly for successive gluon branchings during the parton cascade. Monte Carlo simulations including coherence via AO are available for both initial and final state parton evolution.

Evidence has been reported^{8,9} for color coherence effects in $p\bar{p}$ interactions by DØ and CDF through measuring spatial correlations between soft

and leading- E_T jets in multi-jet events. In this paper we report updated results from the $D\bar{D}$ analysis. A complementary $D\bar{D}$ investigation is also reported here which is sensitive to both perturbative interference effects and the non-perturbative fragmentation process, which can mimic color coherence effects. In this study, soft particle distributions in W +jet events are examined. This is the first time color coherence effects are studied using W bosons and jets.

2.1 Multi-jet Analysis Method

This analysis selects events in which the associated radiation is sufficiently energetic to form additional soft jets. Events studies are those with at least three reconstructed jets, ordered in E_T such that $E_{T1} > E_{T2} > E_{T3}$. The angular distribution, in (η, ϕ) space, of the third jet around the second jet was measured using the polar variables $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $\beta = \tan^{-1}(\frac{\text{sign}(\eta_2) \cdot \Delta\phi}{\Delta\eta})$; where $\Delta\eta = \eta_3 - \eta_2$ and $\Delta\phi = \phi_3 - \phi_2$, in a search disk of $0.6 < R < \pi/2$ (see Fig. 2). The expectation from color interference is that third jet production will be concentrated primarily in the event plane (defined by the second jet and the beam - $\beta = 0, \pi, 2\pi$) with an accompanying depletion in the regions transverse to the event plane ($\beta = \pi/2, 3\pi/2$).

The data angular distributions are compared to particle shower level Monte Carlo simulations (ISAJET¹⁰, HERWIG and PYTHIA¹¹). ISAJET incorporates no interference effects. HERWIG and PYTHIA incorporate interference effects through AO. PYTHIA further allows the user the choice of not implementing AO and allows either string or independent fragmentation. The data are also compared to the predictions of JETRAD.

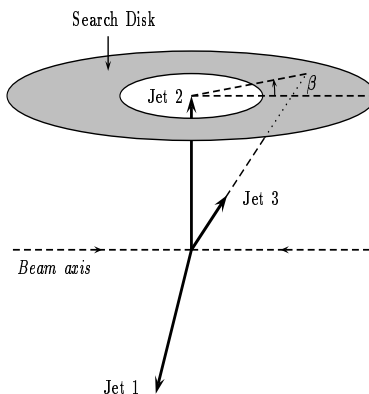


Figure 2: Three-jet event topology illustrating the search disk (gray area) for studying the angular distribution of the softer third jet around the second leading- E_T jet.

2.2 W +jet Analysis Method

In W +jet events, the pattern of soft particles is measured around both the W boson and the opposing jet in order to observe interference effects. The colorless W boson does not contribute to color coherence effects – events with a W boson therefore provide a template against which the pattern around a jet may be observed. This comparison alleviates global detector and underlying event effects. Soft particles in the collider data are approximated in this analysis by projective calorimeter towers (columns of cells of area $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ projecting outward from the center of the detector) with $E_T > 250\text{MeV}$. This threshold was chosen in order to minimize contributions from low-energy calorimeter noise.

Events with the decay $W \rightarrow e + \nu$ are used in this analysis. The W boson is reconstructed from the decay products, resulting in a twofold ambiguity in the W boson rapidity (y_W) due to a similar ambiguity in the neutrino p_Z . Monte Carlo studies have shown that the smaller $|y_W|$ is correct approximately 2/3 of the time, so this is the solution chosen. This choice is also made in the Monte Carlo for consistency. The opposing jet is tagged by selecting the highest- E_T jet in the event. Annular regions similar to those used in the multi-jet study are drawn around both the W boson and the jet in (η, ϕ) space.

The multiplicity of towers above 250MeV is measured in these annular regions using the polar variables $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $\beta_{W,Jet} = \tan^{-1}\left(\frac{\text{sign}(\eta_{W,Jet}) \cdot \Delta\phi_{W,Jet}}{\Delta\eta_{W,Jet}}\right)$ ($\Delta\eta_{W,Jet} = \eta_{Tower} - \eta_{W,Jet}$ and $\Delta\phi_{W,Jet} = \phi_{Tower} - \phi_{W,Jet}$) in a search disk of $0.7 < R < 1.5$. In order to minimize statistical uncertainties, the annuli are folded about the ϕ symmetry axis, thereby reducing the β range to $0 - \pi$. The jet-side distribution is then divided by the W -side distribution. We expect the resulting distribution to exhibit a depletion in the transverse plane relative to the event plane due to color interference on the jet-side.

The data angular distribution is compared to PYTHIA particle level Monte Carlo simulation with color coherence effects turned off and on with string and independent fragmentation. To determine the level of residual η -dependent detector effects in the measured patterns, minimum bias events are compared to the W +jet data. In the minimum bias sample, locations for a fake W boson and fake jet are placed randomly in each event, weighted to reflect real W +jet topology. The same analysis procedure is then applied to these events.

3 Event Selection

The data for the multi-jet analysis were collected during the 1992–1993 initial run of the DØ experiment. The jets were reconstructed using the cone algorithm with radius $R=0.5$ (radius reduced from 0.7 to increase available phase space for third-jet production). The highest- E_T jet in each event was required to have $E_T > 115$ GeV to avoid trigger biases. The third jet was required to have $E_T > 15$ GeV. The interference effects were studied when the second leading- E_T jet was central ($|\eta_2| < 0.7$) or forward ($0.7 < |\eta_2| < 1.5$). The two leading jets were required to be in opposite ϕ hemispheres.

The data for the W +jet analysis were collected during the 1994–1995 run of the DØ experiment. Candidate $W \rightarrow e + \nu$ events were required to have at least one jet reconstructed using the cone algorithm with $R=0.7$ with $E_T > 8$ GeV. The W boson and tagged jet were restricted in rapidity and η , respectively, to ± 0.5 and were required to be in opposite ϕ hemispheres. The z component of the event vertex was restricted to $|z| < 20$ cm to retain the projective nature of the calorimeter towers.

4 Multi-jet Results

The β distributions from data along with Monte Carlo predictions are shown in Fig. 3. The HERWIG, ISAJET and PYTHIA simulations have been performed at the particle level, whereas the JETRAD predictions are at the parton level. Detector position and energy resolution effects have been included in all Monte Carlo predictions. The Monte Carlo events were subjected to the same requirements as data.

Fig. 3 shows the ratios of the β distributions for the DØ data relative to the several Monte Carlo predictions for both central ($|\eta_2| < 0.7$) and forward ($0.7 < |\eta_2| < 1.5$) regions. The absence of color interference effects in ISAJET results in a disagreement with the DØ data distributions. The data show a clear excess of events compared to ISAJET near the event plane ($\beta = 0, \pi, 2\pi$) and a depletion at the transverse plane ($\beta = \frac{\pi}{2}, \frac{3\pi}{2}$), as expected from coherent radiation effects. However, HERWIG, which models interference effects, agrees well with the data. From the DATA/PYTHIA comparisons we see that when we turn off the color coherence effects, PYTHIA disagrees with the data, whereas it agrees better when the coherence effects are turned on with the other properties of the simulator being the same. Lastly, NLO QCD describes the coherence effects seen in data reasonably well as shown by the DATA/JETRAD comparisons.

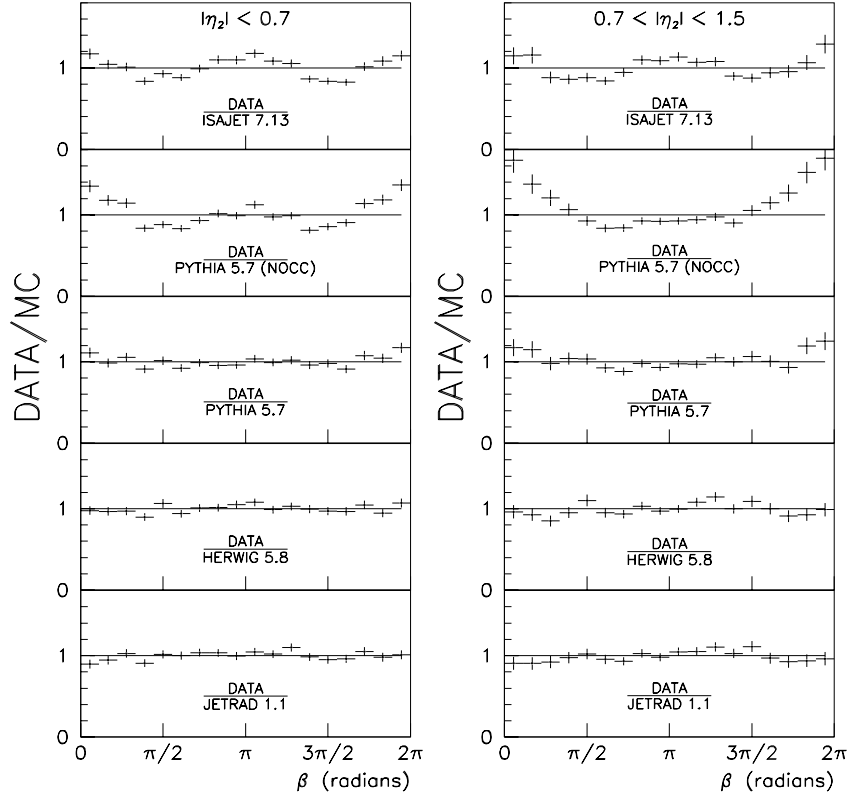


Figure 3: Preliminary comparisons of the data β distributions for central ($|\eta_2| < 0.7$) and forward ($0.7 < |\eta_2| < 1.5$) jets to the predictions of HERWIG, ISAJET, PYTHIA(with and without color coherence effects), and JETRAD. The error bars shown include statistical errors only.

5 W +jet Results

Ratios of the data tower distributions for the jet annular region relative to the W boson annulus are shown in Fig. 4a for W +jet and minimum bias data. When compared to minimum bias data, W +jet data show a significant enhancement in the event plane while approximately agreeing near the transverse plane, where interference is expected to limit additional radiation. In Fig. 4b, particle-level PYTHIA with AO on and string fragmentation is in qualitative agreement with the W +jet data, whereas when AO is turned off and independent fragmentation is employed, there is disagreement with the data. The intermediate level, in which AO is turned off and string fragmentation is

chosen, exhibits behavior similar to the sample with AO, but smaller in magnitude. The relative agreement of this curve with data as compared to PYTHIA with AO will rely upon the ongoing analysis of systematic uncertainties such as calorimeter noise, energy scale and multiple $p\bar{p}$ collisions.

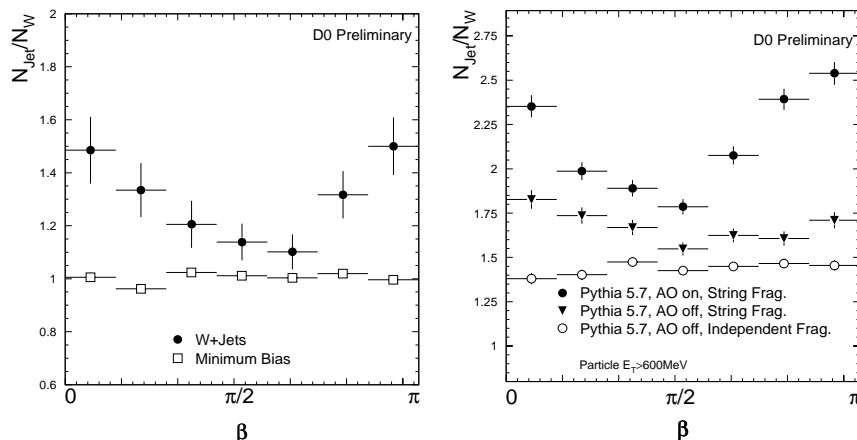


Figure 4: a) Ratios of data folded β distributions Jet/ W in W +jet (filled circles) and minimum bias (open squares) collider data. b) Particle level PYTHIA with AO on and string fragmentation (filled circles), AO off and string fragmentation (triangles), and AO off and independent fragmentation (open circles). All errors are statistical.

6 Conclusions

The first measurement of jet-jet angular decorrelation as a function of pseudorapidity separation has been performed by the DØ collaboration. Results show that the decorrelation seen in data is well reproduced by HERWIG. The JETRAD NLO Monte Carlo predicts too little decorrelation, whereas the BFKL resummation calculation seems to overestimate the effect. The much larger data sample acquired from the most recent collider run will allow us to study the jet decorrelations for lower E_T jets and extend the pseudorapidity coverage to $\Delta\eta = 6$.

Color coherence effects in $p\bar{p}$ interactions have been studied by the DØ collaboration. Using multi-jet events we measured the spatial correlations between the second and the third leading- E_T jets and compared the data distributions to several MC predictions with and without color coherence implementations. Monte Carlo simulations that implement color interference effects (via AO) reproduce the data angular distributions reasonably well, with HERWIG best representing the data. Furthermore, preliminary results indicate that coherence effects as predicted by NLO calculation are also in agreement with the data.

We also presented the first preliminary results on color coherence effects in W +jet events, in which the pattern of soft radiation near a jet is compared with that near a W boson. Data show a depletion of soft particle radiation in the region transverse to the event plane, which is qualitatively consistent with PYTHIA predictions using the AO approximation and string fragmentation.

Acknowledgments

We thank the staffs at Fermilab and the collaborating institutions for their contributions to the success of this work, and acknowledge support from the Department of Energy and National Science Foundation (U.S.A.), Commissariat à l'Energie Atomique (France), Ministries for Atomic Energy and Science and Technology Policy (Russia), CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONA-CyT (Mexico), Ministry of Education and KOSEF (Korea), CONICET and UBACyT (Argentina), and the A.P. Sloan Foundation.

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